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# FLIGHT SIMULATION WITHIN THE FRAME OF MULTIDISCIPLINARY OPTIMIZATION OF LARGE FLEXIBLE AIRCRAFT

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## Abstract

The disciplines flight mechanics / flight control and structural dynamics have to work closely together when large flexible aircraft, such as A340-600 and A3XX, are designed. The flight-control system has to be designed under the constraint that structural oscillation resonances or unacceptable levels of structural loads have to be avoided. Especially the integration of flight control and structural control requires multidisciplinary cooperation. In the potential conflict between handling qualities and minimal structural loads requirements the flight-control law parameters have to be optimized. This paper describes enhancements of real-time flight simulation in order to integrate the pilot into the control loop especially with respect to the effects of cockpit accelerations. The enhancements cover the coupling of rigid body motion and flexible modes in order to analyze the effects of neighboring frequencies, as well as the inclusion of simplified loads computation within the real-time simulation environment. Moreover, a cost-effective way of simulation-model development is presented. This covers model development and testing/validation on a fixed-base engineering flight simulator followed by a proven model transfer onto a six degrees of freedom motion simulator where intensive pilot-in-the-loop investigations can be carried out.

## Nomenclature

$\underline{A}$	state matrix
$\underline{A_L}$	adapted state matrix
a/c	aircraft
APC	aircraft pilot coupling
AS	Aerospatiale
AST	automatic simulation test
$\underline{B}$	control matrix
$\underline{B_L}$	adapted control matrix
$\underline{C}$	output state matrix
$\underline{C_L}$	adapted output state matrix
c/g	center of gravity
CIFSI	cockpit interface simulation
$\underline{D}$	output control matrix
$\underline{D_L}$	adapted output control matrix
DA	DaimlerChrysler Aerospace Airbus
FAR	federal aviation regulations

$\underline{F}_{aero}$	vector of aerodynamic forces and moments
$\underline{F}_{gear}$	vector of forces and moments due to l/g
$\underline{F}_{thrust}$	vector of engine forces and moments
$\underline{F}_{weight}$	vector of gravity forces
FBW	fly by wire
FCS	flight control system
fm	flight mechanical
$G_{nonlinear}$	function of forces and moments
H	altitude
$\underline{I}$	moments of inertia
IRS	inertial reference system
JAR	joint aviation regulations
l/g	landing gear
Ma	mach number
$n_y$	lateral load factor
$n_z$	longitudinal load factor
p	pitch rate
q	roll rate
r	yaw rate
R/A	radio altitude
TUB	Technical University Berlin
$\underline{u}$	control vector
$\underline{x}_e$	vector of elasticity states
$\underline{x}_r$	vector of rigid a/c states (flight mechanics)
$\underline{x}_r$	vector of rigid a/c states (NASTRAN based)
$\underline{y}$	output vector
$\underline{\phi_L}$	interfacing matrix for $\underline{x}_r$
$\phi$	roll angle
$\theta$	pitch angle
$\psi$	yaw angle

## Indices:

e	due to elasticity
ee	effect on elasticity due to elasticity
ef	effect on elasticity due to fm rigid a/c motion
er	effect on elasticity due to rigid a/c motion
f	due to fm rigid a/c motion
ff	effect on fm rigid a/c motion due to fm rigid a/c motion
f	body fixed axes
k	kinetic track fixed axes
r	due to rigid a/c motion
re	effect on rigid a/c motion due to elasticity
rr	effect on rigid a/c motion due to rigid a/c motion
yf	effect on output values due to fm rigid a/c motion

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## 1. Introduction

There is a correlation between aircraft size and the frequencies of the elastic modes i.e. the bigger an aircraft, the lower the frequencies. Large flexible aircraft have elastic modes in a frequency region which potentially overlaps with piloting activity. Therefore the flight control systems (FCS) of these aircraft have to be designed such that aircraft pilot coupling (APC) due to elasticity is impossible in every flight condition. Moreover with today's fly by wire (FBW) flight control technology there is potential for active control of the lower frequency elastic modes. Such active control is under development (see also /1/ and /2/) for large transport aircraft to be certified under JAR 25 / FAR 25. A major challenge of such active control development consists of the requirements being driven interdisciplinary by structural dynamics and handling qualities.

Traditionally, besides crew training, flight simulation is a tool in the discipline of flight mechanics which aims to achieve good handling qualities of new aircraft designs before first flight. This includes simulation usage for FCS development and testing. Flight simulators provide the possibility to bring the pilot into the control loop in real time. Embedded into the technology framework called 3E-Flexible-Aircraft, the Airbus partners are expanding flight simulation utilization into the aeroservoelastic design loop. The target is to identify and eliminate tendencies of APC due to a/c elasticity early in the development process. Inherent to the fact that frequencies of elastic modes are higher than frequencies of rigid a/c response, moving flight simulator utilization is a must. Development flight simulators with a motion system are very rare.

Located at Technical University Berlin there is a special A330/A340 training flight simulator featuring a doubled simulation computer which can be run alternatively instead of the certified, sealed training computer. Therefore the simulator is also accessible for scientific tasks. This accessibility to development engineers allows for varying a/c models as well as systems simulations to be implemented. Nevertheless, due to the limited, slotted access to this moving flight simulator, the main development work is better performed within a conventional fixed base flight simulation environment. Therefore a robust and efficient model transfer from the fixed base engineering onto the moving flight simulator is a major achievement.

The necessary interdisciplinary cooperation starts with the development of a mathematical model of large flexible aircraft. The modeling approach presented in this paper is distinguished by being generally exact in the core frequency regimes of the according disciplines. This means on the one hand that low frequency rigid body motion as well as higher frequency aircraft elasticity can be computed with the best algorithms available for the according physical problem. On the other hand the dynamic coupling between rigid body motion and elastic modes is fully included within the model. Such a solution can be achieved mathematically by elaboration of appropriate interfacing between the model contributions from the core activities of the concerned disciplines.

But this achievement is based strongly on good interdisciplinary cooperation of the relevant specialists, providing the proven and advanced know-how of their disciplines. The complexity of interdisciplinary rigid/elastic a/c modeling has been found mainly in the different

specialized views between the handling quality and structural dynamics disciplines, due to the problems traditionally being addressed and the mathematical solving methods usually being applied. This situation is accompanied by the fact that, because already the complex core disciplines alone require specialist's know-how to cover the a/c behavior mathematically, it is nearly impossible for individuals to acquire sufficient knowledge and experience in each area, to achieve the mentioned model exactness in the lower, higher and in the intermediate frequency regime, where the disciplines and physical phenomena are overlapping.

Keeping the common goal of interdisciplinary harmonized modeling and control problem solving in mind, the specialists first need to exchange a sufficient, but limited knowledge of their traditional mathematical abstractions and solving methods. This includes usual methodological prerequisites, assumptions, approximations and limits. It is advantageous, when the participating specialists generally can remain within their traditional way of thinking. Then appropriate, harmonized interfacing and data exchange is the key, in order to achieve the interdisciplinary model architecture which allows flight mechanics as well as aeroelastics and loads disciplines to consider and implement the common model as an add-on to their traditional approaches, algorithms and software. Model application on each side leads consequently to comparing calculations and a fruitful, slightly iterative model fine tuning.

Specific adaptations and simplifications due to the needs of the varying model applications are jointly generated and cross checked between the disciplines. For example the real time calculation requirement for the flight simulator application leads to a limited number of elastic modes which can be taken into account. While the necessary selection and application of mode reduction methodology has been found best practicable by aeroelastics specialists, the real time specific coding as well as the integration method evaluation and selection profited by the flight mechanics' experience.

Concerning the interdisciplinary cooperation process which relies strongly on massive data exchange, automation has been found very important. Interdisciplinary model preparation and coding as well as model transfer between the flight simulators have been developed such that automatic software processes resulted immediately. This is already advantageous as long as the mentioned iterative fine tuning is performed.

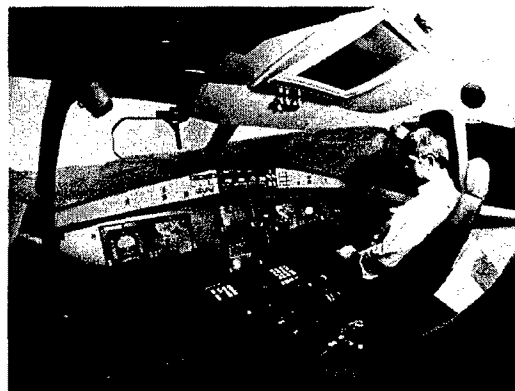
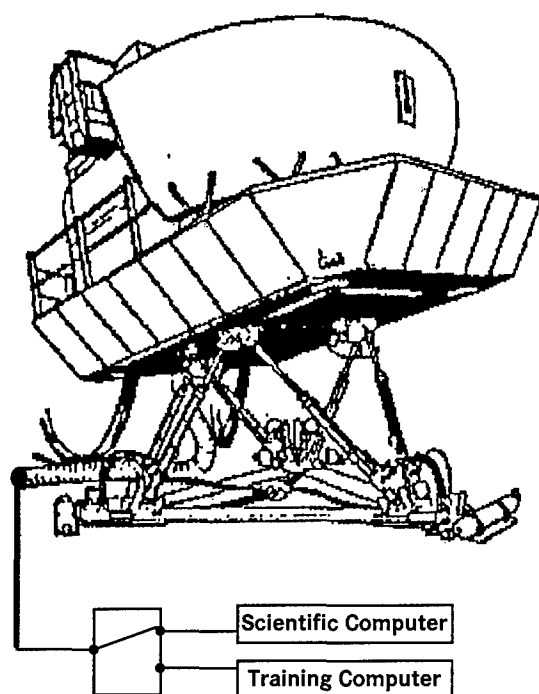


Figure 1: Development Flight Simulator Cockpit



**Figure 2:** Motion Flight Simulator & Scientific Computer

## **2. Flight Simulation Activities**

In order to ensure that aircraft elasticity does not lead to unfavorable coupling with pilot in the loop control, flight simulation can be an advantageous tool from early in the design process onwards. With respect to the efforts of supporting the aeroservoelastic design process introduced before, there are the following areas of flight simulation contributions:

### **2.1 Support for off-line Stability Calculations**

The bio-mechanical coupling resulting from cockpit accelerations due to a/c elasticity has been addressed here. The outcome are transfer functions from cockpit accelerations to side-stick inputs, via seat and pilot. These transfer functions were included into aeroelastic stability calculations. In the past such specialized flutter calculations already considered the flight control system by inclusion of sensor feed-backs and flight control laws, but closing the loop via the pilot is new.

Flight simulation has played its role for the generation of the cockpit-to-stick transfer functions. In the moving flight simulator a series of tests with Airbus line and test-pilots was performed. Separated between low and high gain piloting tasks (attitude hold and landing approach respectively), there were artificial cockpit accelerations superimposed with the motions known from training simulators, especially without elastic modes in the a/c model. With the intention to have common excitations for all the tests, sweeps of known frequency behavior were imposed in z- as well as in y-direction. So here the flight simulator was used as a simple shaker, but with the real cockpit environment and pilots in real flying conditions.

Since the data acquisition, evaluation and interpretation was mainly performed by the cooperating partners from Technical University Berlin, and since the results can fill an extra paper at a later time, here only some general highlights shall be summarized:

- Obvious from the beginning was that significant coupling would occur only when the pilot has a tight grip on the side-stick. This was realized during the experiments by a mistrim (could be switched on/off) in pitch and roll axes within the a/c aerodynamic model, requiring to fly around a non-zero side-stick position. Since FBW control laws would compensate for that mistrim, flying in direct law was a must.
- The differentiation between lower and higher gain tasks was negligible in comparison to the differences between mentally lower and higher gain pilots. In order to investigate the worst case situation, the highest amplitude transfer functions should be considered in the off-line calculations.
- Understanding the seat as a damped spring-mass-system, typical eigenfrequencies around 4 Hz have been discovered.
- Interesting cross couplings between z-accelerations and roll-stick-inputs and (less severe) vice versa between y-accelerations and pitch-stick-inputs were observed, which should not be neglected in future aeroelastic stability calculations, since here a path to potential excitement of each (lateral and longitudinal) elastic mode is existent.

### **2.2 Inclusion of elastic Modes**

In order to prepare piloted tests with respect to APC due to elasticity, flight simulators must include the effects resulting from elastic mode excitations. Two main kinds of additional signals have to be calculated:

- Cockpit accelerations being composed from rigid a/c movement and from elastic deformations, in order to be realized by the flight simulator's motion system.
- Sensor signals including elasticity contributions (mainly IRS signals) as load factors ( $n_x$ ,  $n_z$ ), rotational rates ( $p$ ,  $q$ ,  $r$ ) as well as attitudes ( $\phi$ ,  $\theta$ ,  $\psi$ ) to be interfaced with the flight control laws and for cockpit vision and indications.

Additionally the height of the landing gear above ground, including the variations due to the elastic a/c structure is valuable for improved touch down simulations. Once the calculation of the elastic modes and its coupling with the rigid a/c movement is included within the flight simulation software, all the above mentioned signals can be gained as output values. Up to now incorporation of the cockpit accelerations is completed.

It is evident that for utilization in flight simulators the a/c model has to be represented in time domain. The mathematical setup of the interdisciplinary model is described in chapter 3. The related software generation and transportation process follows in chapter 4.

Due to the fact that the flight simulator application requires real time calculation capability, the following aspects are of special importance:

- Computing power is a limiting factor. It has been a big step forward that both involved flight simulation environments (fixed base engineering as well as the moving-simulator) benefited from computer hardware upgrades during the elasticity inclusion phase up to the current status. The openness to such upgrades, following the still rapidly improving hardware development will once more be welcome when future simulation model enhancements (see chapter 5) will be incorporated.
- Special software coding, adapted to the real time requirement, is still favorable. Especially since the usage of intensive optimization during software compilation has once more been found being not adequately robust for flight simulation application, real time adaptations on source code level are valuable. Despite inline coding, with respect to larger matrix operations within the included elastic mode calculations, it has been achieved to save about 70% of computation time by automatic elimination of all permanent multiplication-by-zero-operations on source code level.
- Investigation for the most advantageous numerical integration method pays off. For the elasticity calculation part of the flight simulator application, the 2<sup>nd</sup> order Adam's Bashforth algorithm

$$y(t) = y(t-1) + \left( \frac{3 \cdot x(t) - x(t-1)}{2} \right) \cdot \Delta t \quad (1)$$

has been proven to be suited best. It offers a good compromise between numerical stability and total computation time. The according cycle time of 5.55 msec resulted from a general 60 Hz requirement due to the moving simulator environment and from a threefold computation of the elastic modes within this frame.

- Nevertheless, the number of calculated elastic modes has to be limited in comparison with usual off-line structural dynamics (loads and flutter) calculations. Mode reduction methods are a separate field of science. For the present implementation Karpel's method /4/ has been used by the structural dynamics specialists.

The realized inclusion of cockpit accelerations due to elasticity has been presented to pilots in the moving flight simulator. The feedback has been positive. Elastic vibrations have been found similar to the behavior known from slightly gusty conditions. Measured simulator cockpit accelerations show good coincidence with the commanded signals from the output of the included elastic mode calculations.

### 2.3 Inclusion of simplified Loads Computations

For the ability to investigate the influences of FCS designs on structural loads by piloted flight simulations, real time capable loads computations are also included into the flight simulation software. This is not intended for the reproduction of design loads, but for the judgment of future loads control functions and for the determination of the

dependencies (sensitivities) of loads from critical, interdisciplinary relevant FCL parameters already in early design phases. The loads algorithms have been simplified by the contributing specialists, in order to meet the real time capability requirement.

At this stage the interfaced loads package is separate from the inclusion of the aeroelastic modes mentioned before. Explicit modes or loads computation can be switched on alternatively only. In the future both structural dynamics model contributions shall be merged. The reason for the current intermediate status is the already mentioned intention within the interdisciplinary cooperation that the participating specialists evolutionary contribute and enhance their proven methodologies while avoiding revolutionary forced changes of their proven ways of thinking.

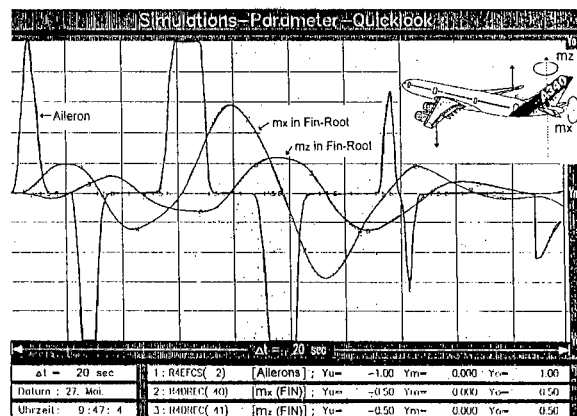


Figure 3: Quicklook on loads parameters during simulation

### 2.4 Simulator Motion System Validation

Before reliable predictions on APC tendencies with respect to new large flexible aircraft can be gained through piloted moving flight simulator investigations, it has been found favorable to validate the capability of the simulator's motion system being signaled by the enhanced a/c model. Besides data recordings of measured accelerations, the real proof shall be the reproduction of elasticity phenomena known from the A340-300 flight test phase. Doing this successfully will provide confidence in the addressed APC prediction capabilities of the enhanced simulation tool. Because motion system performance decreases with increasing frequencies, and because the mode frequencies of the future large flexible a/c, such as A340-600 and A3XX, will be lower than of A340-300, there will be sufficient certainty.

At this stage preparation work (including hardware based FCL implementation) for the phenomenon reproduction in cooperation between AS, DA and TUB is nearly completed, and pilots soon will be invited for the according simulator sessions.

### 2.5 Early APC Avoidance

As introduced, ensuring that new aircraft-, FCS- and FCL- designs avoid tendencies for occurrence of APC due to elasticity, improved real time flight simulation shall provide experimental assistance. This support is regarded as highly efficient, because designs can be analyzed and optimized

already in early design phases, especially through the pilot in the loop capability before first flight. Within the aeroservoelastic design process, especially parameter tuning for acceptable elastic mode amplitudes and minimized loads in conjunction with good handling qualities can be judged and controlled by the feed-backs from flight simulator sessions. It also brings pilots' expertise into the design loop earlier. Future integral flight control laws can be optimized with respect to their effectiveness becoming interdisciplinary approved.

The current status of work is preparedness according to modeling and simulation setup process, as described in the following chapters. Impressive is, when flying the elastic A340-300 in the moving simulator, the FCL behavior with respect to elasticity can be felt hands-on. For example when flying an approach and trying to excite elastic modes on purpose via the side-stick (note: This is no APC!), and when passing through 500 ft R/A, an FCL internal switching, affecting elasticity becomes immediately obvious due to the motion impression. This capability for direct behavior identification, related to elasticity, is the driving factor for the described activities, targeting piloted motion flight simulator investigations. Additionally, such experiments should be avoided in the real aircraft because unnecessary loads would contribute to structural fatigue.

### 3. Aircraft Modeling

As indicated before, the achieved interdisciplinary a/c modeling is the joint outcome of contributions from flight mechanics as well as structural dynamics disciplines. The intention to couple the algorithms of rigid a/c movement and elastic modes by appropriate interfacing lead to a summary of the different traditional methodologies according to **table 1**.

Flight Mechanics & Maneuver Loads	Aeroelastics & Gust Loads
formulation in time domain	formulation in frequency domain
nonlinear equations of motion	linear equations of motion
absolute states	states as small deviations
nonlinear flight simulation	possibility of state space simulations after transformation into time domain
limited to motion of c/g, plus geometrical relations as for cockpit-, l/g- or tail-motion	direct access to motion of any grid point

**Table 1:** Different Methodologies

The following interdisciplinary methodology has been developed from the traditional ones within aeroelastics and flight mechanics. For the interfacing cooperation the agreed common coordinate system is body-fixed, originating in the c/g. The result is open for direct loads computation as well, but this is future work. Because formulation in time domain

is a prerequisite for flight simulation, transformation of the aeroelastic mode equations from frequency domain into time domain is necessary, but was proven in the past.

Therefore the aeroelastic state space model formulation

$$\dot{\underline{x}}_e = \underline{A}_{ee} \cdot \underline{x}_e + \underline{B}_e \cdot \underline{u} \quad (2)$$

is one starting point. In order to present the formula easier to survey, gust disturbances are omitted here. Linearized 6 degrees of freedom rigid a/c motion can be written correspondingly:

$$\dot{\underline{x}}_r = \underline{A}_{rr} \cdot \underline{x}_r + \underline{B}_r \cdot \underline{u} \quad (3)$$

The vector  $\underline{x}_r$  is part of the aeroelastic discipline's contribution. Per se it is not identical with the vector  $\underline{x}_r$  within the flight mechanics formulation (see below). The vector  $\underline{x}_r$  is the best possible approximation of  $\underline{x}_r$ . It results from inclusion of the rigid a/c modes into the structural dynamics tool called NASTRAN and from a specialized mode approximation supported vice versa by flight mechanics contributions of the exact modes. According to /3/ a coupled state space model is determined:

$$\begin{bmatrix} \dot{\underline{x}}_r \\ \dot{\underline{x}}_e \end{bmatrix} = \begin{bmatrix} \underline{A}_{rr} & \underline{A}_{re} \\ \underline{A}_{er} & \underline{A}_{ee} \end{bmatrix} \cdot \begin{bmatrix} \underline{x}_r \\ \underline{x}_e \end{bmatrix} + \begin{bmatrix} \underline{B}_r \\ \underline{B}_e \end{bmatrix} \cdot \underline{u} \quad (4)$$

Equation (3) can be rewritten for the exact flight mechanical behavior:

$$\dot{\underline{x}}_f = \underline{A}_{ff} \cdot \underline{x}_f + \underline{B}_f \cdot \underline{u} \quad (5)$$

Now the specialty of the cooperative interdisciplinary model is a transformation of equation (4) with two specified attributes:

- The vector  $\underline{x}_r$  must follow stationary the path of  $\underline{x}_f$ .
- Therefore the coupling matrix  $\underline{A}_{re}$  (rigid due to elastic) may only lead to dynamic deviations of  $\underline{x}_r$  around the path of  $\underline{x}_f$  with frequencies upwards from the lowest frequency elastic mode.

The stationary effects of elasticity onto  $\underline{x}_f$  and  $\underline{x}_r$  have been found to be best incorporated by the flexible factors, which are part of the flight mechanical model contribution; here represented within  $\underline{x}_f$ . The transformation of equation (4), for which the aeroelastics specialists perform a special eigenvector calculation, leads to a formulation with  $\dot{\underline{x}}_f$  as an additional input:

$$\begin{bmatrix} \dot{\underline{x}}_r \\ \dot{\underline{x}}_e \end{bmatrix} = \begin{bmatrix} 1 \\ \underline{\Phi L}_{ef} \end{bmatrix} \cdot \dot{\underline{x}}_f + \begin{bmatrix} \underline{A L}_{rr} & \underline{A L}_{re} \\ \underline{A L}_{er} & \underline{A L}_{ee} \end{bmatrix} \cdot \begin{bmatrix} \underline{x}_r \\ \underline{x}_e \end{bmatrix} + \begin{bmatrix} \underline{B L}_r \\ \underline{B L}_e \end{bmatrix} \cdot \underline{u} \quad (6)$$

An output vector  $\underline{y}$  results from integration of  $\dot{\underline{x}}_r$  and  $\dot{\underline{x}}_e$ :

$$\underline{y} = \underline{\Phi L}_{yf} \cdot \dot{\underline{x}}_f + \underline{C L}_r \cdot \underline{x}_r + \underline{C L}_e \cdot \underline{x}_e + \underline{D L} \cdot \underline{u} \quad (7)$$

The output vector  $\underline{y}$  gives cockpit accelerations, sensor signals,  $l/g$  above ground deviation due to elasticity and any other grid point motion needed for flight simulator application.

The main feature that  $\underline{x}_f$  does not receive a backward coupling from the mode equations (6) and (7), allows for a replacement of  $\dot{\underline{x}}_f$  from the linear equation (5) by the same vector being calculated nonlinear:

$$\dot{\underline{x}}_f = G_{\text{nonlinear}}(\underline{F}_{\text{aero}}, \underline{F}_{\text{thrust}}, \underline{F}_{\text{weight}}, \underline{F}_{\text{gear}}) \quad (8)$$

The function  $G_{\text{nonlinear}}$  can be derived from the flight mechanical equations of motion; typical translatory equation:

$$\begin{bmatrix} \dot{u}_k \\ \dot{v}_k \\ \dot{w}_k \end{bmatrix}_f = \frac{1}{m} \begin{bmatrix} X^A \\ Y^A \\ Z^A \end{bmatrix}_f + \frac{1}{m} \begin{bmatrix} X^F \\ Y^F \\ Z^F \end{bmatrix}_f + \begin{bmatrix} -\sin \Theta \\ \sin \Phi \cos \Theta \\ \cos \Phi \cos \Theta \end{bmatrix} \cdot g - \begin{bmatrix} q_k w_k - r_k v_k \\ r_k u_k - p_k w_k \\ p_k v_k - q_k u_k \end{bmatrix}_f \quad (9)$$

And typical rotatory equation:

$$\begin{bmatrix} \dot{p}_k \\ \dot{q}_k \\ \dot{r}_k \end{bmatrix} = I_f^{-1} \cdot \begin{bmatrix} L^A + L^F \\ M^A + M^F \\ N^A + N^F \end{bmatrix}_f - \begin{bmatrix} q_k r_k (I_z - I_y) - p_k q_k I_{zx} \\ r_k p_k (I_x - I_z) + (p_k^2 - r_k^2) I_{xz} \\ p_k q_k (I_y - I_x) + q_k r_k I_{xz} \end{bmatrix}_f \quad (10)$$

with:

$$\underline{F}_{\text{aero}} = [X^A, Y^A, Z^A, L^A, M^A, N^A]^T \quad (11)$$

$$\underline{F}_{\text{thrust}} + \underline{F}_{\text{gear}} = [X^F, Y^F, Z^F, L^F, M^F, N^F]^T \quad (12)$$

$$\underline{F}_{\text{weight}} = \begin{bmatrix} -\sin \Theta \\ \sin \Phi \cos \Theta \\ \cos \Phi \cos \Theta \end{bmatrix} \cdot g \quad (13)$$

The equations (9) and (10) are typically implemented within flight simulators. They are the source for interfacing with the elasticity. But there is a significant distinction to be interpreted before deriving  $\dot{\underline{x}}_f$  in equation (8) directly.

This distinction comes from the fact that the linear state space model (6) describes deviations from a single flight condition. Such a working point is defined by a certain (H, Ma) combination. Therefore  $\dot{\underline{x}}_f$  in (8) corresponds with the absolute values in (9) and (10) being initialized at the

mentioned flight condition and only the deviations being interfaced. For the reproduction of known elasticity phenomena in the flight simulators such proceeding can be sufficient.

Nevertheless for future investigations, focusing on APC due to elasticity, a wider simulation capability within the entire flight envelope is desirable. This will be achieved by consideration of larger numbers of flight condition related state space models and by sophisticated interpolation methodology. Related preparation work is documented in /5/, where the required computation power and the numerical complexity of this task are becoming visible (see also chapter 5).

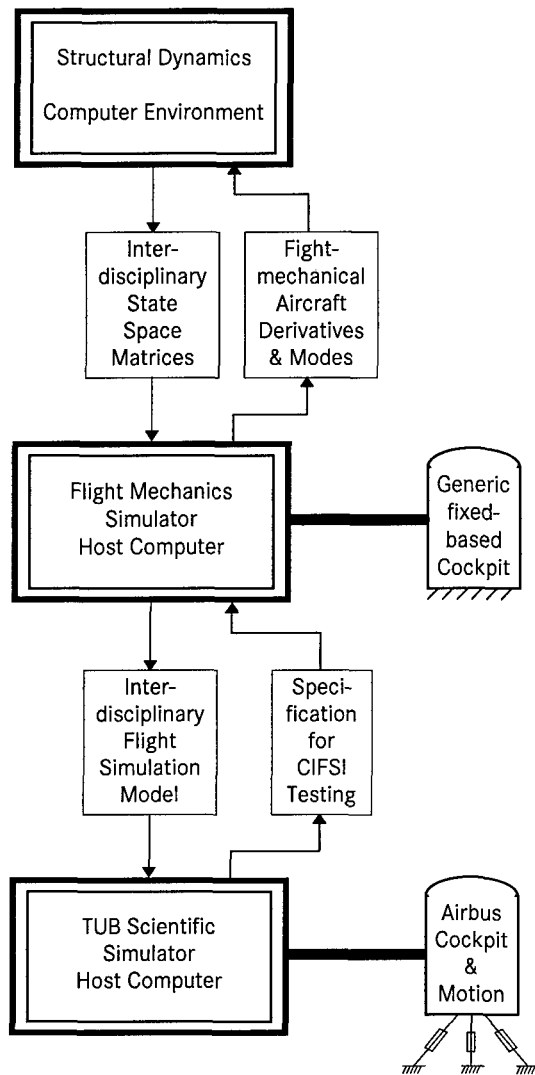
The presented interdisciplinary modeling methodology is characterized by two peculiarities:

- Flight mechanics as well as structural dynamics disciplines can both implement the interdisciplinary model as an add-on to their traditional modeling. Flight mechanics interface the equations (6) and (7) via  $\dot{\underline{x}}_f$ , as described. Structural dynamics receive a linearized rigid a/c simulator-model according to equation (5), and then they can perform comparing off-line calculations in their proven environment.
- The interdisciplinary model features exactness at both ends of the common frequency regime. Stationary and low frequency rigid modes are dominated by the vector  $\underline{x}_f$ . Calculation of  $\underline{x}_f$  is not influenced by the model upgrade. Higher elastic mode frequencies (vector  $\underline{x}_e$ ) are correct as well, because the eigenvector calculation between equation (4) and (6) leaves them unchanged. Through parallel calculation of  $\underline{x}_f$ , also the intermediate frequency regime and the full rigid/elastic coupling is incorporated with best possible fidelity. The deviation of the c/g motion, due to elastic modes and due to the coupling, is permanently accessible by the difference  $\underline{x}_r - \underline{x}_f$  which stationary fades to zero.

#### 4. Work Process

The development of the interdisciplinary modeling methodology has been performed in close cooperation between flight mechanics and structural dynamics specialists. Comparative calculations were performed at all levels of progress. Automation of data generation and transfer as well as software code generation and transfer has been incorporated already from the beginning of the development. The process leads to piloted investigations in the six degrees of freedom, moving flight simulator located at TUB. Sessions in the moving flight simulator are slotted into it's main utilization as a training device. The limited accessibility and the higher costs per simulation hour lead to the decision, to develop and transfer fully tested models to Berlin.

Development and testing of the flight simulation software was carried out at DA's engineering flight simulator, featuring a fixed base generic cockpit with vision and sound. Here accessibility is better and costs are lower. This development simulation environment also has been used in parallel for off-line calculations. The automatic simulation test (AST) is a tool, which has been adapted especially for the checkout of the interdisciplinary modeling. It allows simulations to be run by scenarios predefined on a text file level and leads directly to specific plots.



**Figure 4:** Cooperation and data/software transfers

From the point of view of flight mechanic the following steps belong to the creation of a running simulation, after a common decision for a flight condition to be investigated:

- Calculation of flight mechanic a/c derivatives and rigid a/c modes; delivery to structural dynamics in an agreed format.  
(Automation: Pressing a button and sending an e-mail)
- Structural dynamics specialists calculate the elastic modes and the full coupling (by a complex and intensive off-line computation), thereby generating the values of the matrices presented in the equations (6) and (7); delivery of these values back to flight mechanics in an agreed format.  
(Automation: Pressing a button, waiting and sending an e-mail)
- Real time capable coding of the equations (6) and (7).  
(Automation: Pressing a button and getting in return a FORTRAN subroutine ready for compilation)
- Implementation of this routine into DA's engineering flight simulator environment, where the a/c specific simulation and the necessary interfacing are ready for service.  
(Automation: Copy onto the simulator HOST computer,

compilation and link)

- Intensive off-line automatic simulation testing (AST) and real-time tests in the development simulator with engineering pilots in the loop, widely covering the targeted model functionality and using CIFSI (see below) in order to ensure a seamless model transfer onto the moving flight simulator.
- Model transfer: TUB specific software adaptation, compressing extraction, centralization and final development simulator check.  
(Automation: Press a button and copy on a disk)
- Running the transferred model on the moving simulator and being prepared for piloted evaluations related to APC due to elasticity.  
(Automation: Read the software from disk, compile, link and run the simulation)

Software interfacing between the two simulation environments consists of two features (TUB interface and CIFSI). Cooperating specialists from TUB have prepared a FORTRAN interface, based on only two common blocks, which allows for a (now plug and play) integration of any a/c simulation model independently from the otherwise present A330/A340 related systems architecture and interdependence. The software environment of DA's development flight simulator has been connected with this interface in order to make the a/c modeling structure transferable. Initially the software could be switched for running in either environment.

But now, in a second step, the achieved status was further improved. A destined cockpit interface simulation (CIFSI) has been developed which replicates the moving simulator interface already within the development flight simulator. Using CIFSI means that DA's cockpit behaves virtually identically to the cockpit in Berlin. Finally it is this feature which allows for sufficient testing, including testing of the TUB specific interfacing before the model transfer. Besides the mentioned automation, this early, in depth testing capability is the real cost-saver featuring this process and allowing for the seamless a/c simulation model transfer.

## **5. Future Activities**

### **5.1 Large Aircraft Flight Simulation Models**

According to the presented methodologies flight simulation modeling shall be applied on new large flexible aircraft such as A340-600 and A3XX, permanently taking the latest specifications into account. These models shall respectively be transferred onto the moving flight simulator, allowing early detection of possible tendencies for APC due to elasticity and of according impacts on loads.

### **5.2 Further Modeling Improvements**

As indicated before, flight simulation is most useful when the modeling is applicable within the entire flight envelope. The current status, to initialize the dynamic a/c elasticity modeling at certain flight conditions and then simulate nearby (with respect to altitude and Mach number variations), shall be overcome. Since the linear state space modeling of the elasticity part will remain the only one applicable in the foreseeable future, interpolations within a



larger number of state space models is the intended way to proceed.

Introducing investigations on the topic addressing interpolations of such specific state space models have been performed and documented in /5/. Besides the proper definition of absolute states and the related deviations from them, the challenge consists of an inherent coincidence. States and independent interpolation variables partially overlap. For example altitude is the one independent interpolation variable and in parallel it is a state within each single linear model. The other independent interpolation variable, the Mach number, is embedded within each single linear model with even more complexity. The states contain a/c velocity separated into body-fixed axes components, and the velocity of sound is dependent on altitude. Additionally the new interpolation methodology will require a huge amount of computation power for real time capable realization. That's why the presented openness of the involved flight simulation environments with respect to hardware upgrades is so welcome also in the future.

### 5.3 Work on Loads Control Functions

Special functionality for flight control laws, in order to keep loads at low levels, is under development at DA. Feasibility and value of these loads control functions shall also be validated by pilot-in-the-loop sessions utilizing the presented flight simulations within the multidisciplinary aeroservoelastic design process.

### 5.4 Implementation of interdisciplinary FCLs

Finally future flight control laws, improved for the needs of large flexible aircraft, shall prove their effectiveness with respect to the interdisciplinary requirements from structural dynamics and flight mechanics / handling qualities. Piloted flight simulations shall provide support within the design process from early phases onwards and confidence with respect to successful avoidance of APC tendencies due to elasticity, especially before first flight. The intermediate frequency regime, where the rigid a/c motion and the coupled elasticity are overlapping, and where the cooperating disciplines of structural dynamics and flight mechanics come parallel in touch, is the intended area for promising new flight simulation utilization, in particular pilot-in-the-loop simulation including cockpit motions.

## 6. Conclusions

This paper presented an approach to utilize pilot-in-the-loop flight simulation within the aeroservoelastic design process of large flexible aircraft. The intention is avoidance of APC due to elasticity and of excessive loads early during the development and especially before first flight. Successful interdisciplinary cooperation between structural dynamics and flight mechanics has been achieved. The cooperation found a modeling methodology, which can be considered in both disciplines as an add-on to their traditional approaches. It features exactness for rigid a/c motion as well as for the structural modes. In the intermediate frequency regime, where the phenomena are overlapping, highest possible fidelity of the model has been achieved through full coupling of rigid motion and elasticity. Two flight simulators are involved, each providing its advantages. An engineering flight simulator

with a fixed base cockpit is the main software development tool with good accessibility and lower costs. And a special moving flight simulator with a scientific computation facility, allowing variable a/c modeling, is the target for the APC related piloted investigations. A proven model transfer from the development onto the moving flight simulator has been realized to a plug-and-play standard. The interdisciplinary cooperation process profits from automation, being widely designed into all data and software exchange steps from the beginning.

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